

N87-16404

TECHNICAL SESSIONS

Cell Technology

ADVANCED SILICON SHEET

Andrew D. Morrison, Chairman

Eleven presentations were made at this session covering research on silicon-shaped sheet technology.

JPL reported on the FSA-sponsored Fourth Silicon Stress/Strain Workshop held March 18 and 19, 1986, at the University of Kentucky, Lexington, Kentucky. The purpose of this Workshop was to review, coordinate, and assess the progress in understanding and controlling stress and strain during the crystal growth of silicon ribbon.

Westinghouse Electric Corp. reviewed progress in its program to develop the technology of the dendritic web ribbon process. Thermal stress analysis, automated closed-loop control of ribbon growth, and increased ribbon area growth rates were subjects receiving emphasis.

JPL reported on its Web Team activities which are directed toward identifying and attacking problem areas in the growth of dendritic web ribbon, to complement the program at Westinghouse Electric Corp.

Mobil Solar Energy Corp. reviewed progress in its stress and efficiency studies of edge-defined film-fed growth (EFG) material. Effort was concentrated on the definition of conditions that will reduce stress, on quantifying dislocation electrical activity and limits on solar cell efficiency, and on studying the effects of dopants on EFG characteristics.

The Solar Energy Research Institute (SERI) described the work on silicon for high-efficiency solar cells. Topics that were discussed included the contributions made by evaporation and segregation to impurity profiles of float-zone (FZ) crystals, study of the effects of some crystal growth parameters on minority-carrier lifetimes, and defect investigations by x-ray topography.

The University of Kentucky presented results of its work on stress/strain relationships in silicon ribbon. Calculations of stress fields, dislocation densities, and buckling were made; uniaxial tensile tests were made on silicon at 1150°C; and dislocation motion studies were performed.

JPL described in-house work on silicon stress/strain, including the study of fracture mechanics, and on the high-temperature test program in which the low-strain response of silicon sheet materials above 1000°C is being measured and new high-temperature material property data are being determined.

Cornell University reported on their results in the study of high-temperature deformation of dendritic web ribbon, and in the work on measuring oxygen in the material.

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The University of Illinois at Chicago discussed their program which is aimed at developing an understanding of the basic mechanisms of deformation during the lubricated cutting of silicon, and at developing a nondestructive measurement technique for residual stresses in silicon sheet.

Washington University at St. Louis reported on their modeling study of Czochralski (Cz) crystal growth.

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REPORT ON THE FOURTH STRESS STRAIN/WORKSHOP

JET PROPULSION LABORATORY

M. H. Leipold

Purpose

- TO REVIEW, COORDINATE AND ASSESS THE PROGRESS IN UNDERSTANDING AND CONTROLLING STRESS AND STRAIN DURING THE CRYSTAL GROWTH OF SILICON RIBBON

Location

- HOSTED BY THE UNIVERSITY OF KENTUCKY AT LEXINGTON, KY
ON MAR 18-19, 1986

Content

- 12 TECHNICAL PRESENTATIONS BY CONTRACTOR, JPL STAFF AND GUEST SPEAKERS. MEETING ATTENDANCE WAS 25

Technical Background

- NUMEROUS 'LIMITS' TO RIBBON GROWTH RATE EXIST
 - REJECTION OF HEAT OF FUSION
 - MACRO STRESS - ELASTIC OR PLASTIC BUCKLING STRUCTURE
 - MICRO STRESS - INTERNAL DISLOCATION

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Technical Progress

- COMPUTER ANALYSIS OF STRESS AS A FUNCTION OF TEMPERATURE PROFILE
 - CREEP RELAXATION STILL IN QUESTION
- MACRO-DEFORMATION BECOMING TRACTABLE
 - ELASTIC BUCKLING REDUCED WITH BETTER PROFILES
 - PLASTIC BUCKLING SENSITIVE TO DATA FOR HIGH TEMPERATURE MECHANICAL PROPERTIES OF Si
 - SUMINO DATA VERY USEFUL
 - TESTS IN PROGRESS
- MICRO-DEFORMATION SHOWS PROGRESS
 - COMPUTER MODELS NOW DESCRIBE DISLOCATION, MULTIPLICATION & MOTION
 - BETTER DATA NEED
 - NUMBER OF DISLOCATION SOURCES IS INDETERMINANT

Technical Prognosis

- BETTER UNDERSTANDING OF PROCESS IS YIELDING SOME IMPROVEMENTS
- EXISTENCE OF FINITE 'SPEED LIMITS' IS LIKELY
- VARIOUS APPROACHES TO CONTROLLING STRESS EXIST
 - SOLID SOLUTION HARDENING
 - CONTROLLED TEMPERATURE PROFILES ACROSS WIDTH
 - CRYSTAL FRONT NOT PERPENDICULAR TO RIBBON
 - CONTROL OF STRAIN DISTRIBUTION
- PERFORMANCE WINDOW STILL AVAILABLE

SILICON DENDRITIC WEB GROWTH

WESTINGHOUSE ELECTRIC CORPORATION

R. Hopkins

Silicon Dendritic Web Development

Recent Highlights

- Area Rate $10 \text{ cm}^2/\text{min}$, $> 1 \text{ m}$ Length
- Maximum Web Width 7 cm; 6 cm Wide Web Frequently Grown
- 17 m Long Web Grown with Continuous Replenishment
- Closed Loop Control System Successfully Demonstrated
- Growth Initiation from "Web Seeds" Up to 4.5 cm Wide
- Doubled Maximum Weekly Single Web Furnace Output to $47,000 \text{ cm}^2$

Overview of Web Growth Studies

- Area Rate Development

— Thermal Stress Effects:
Elastic Buckling
Plastic Deformation

(R. G. Seidensticker, J. P. McHugh,
J. Spitznagel, S. Y. Lien, R. Hundal,
R. Spreccase)

- Closed Loop Control of Web Growth

(J. Easoz, P. Piotrowski, C. S. Duncan,
F. Przywarty, E. L. Kochka)

- Summary

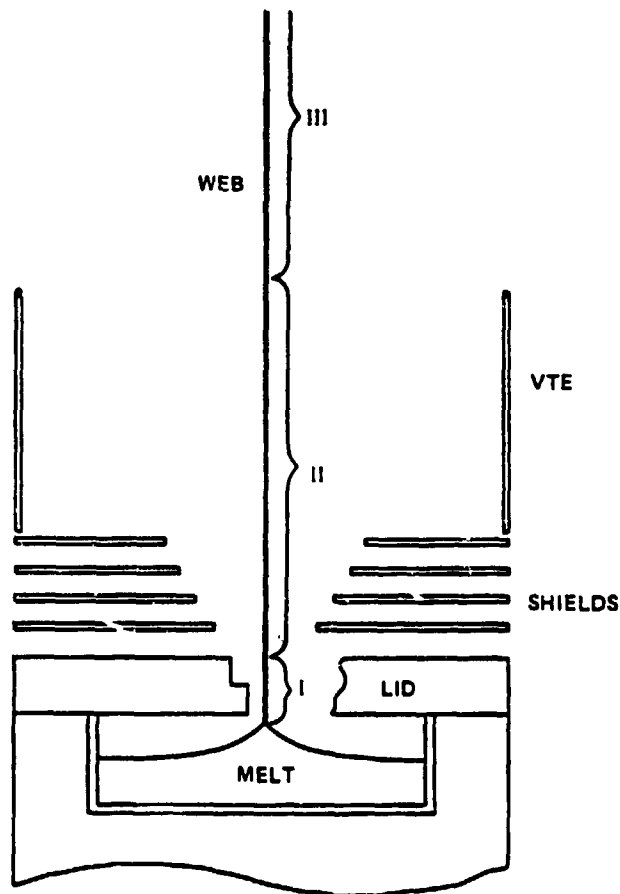
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Silicon Dendritic Web Development Modeling Studies

Elastic Deformation

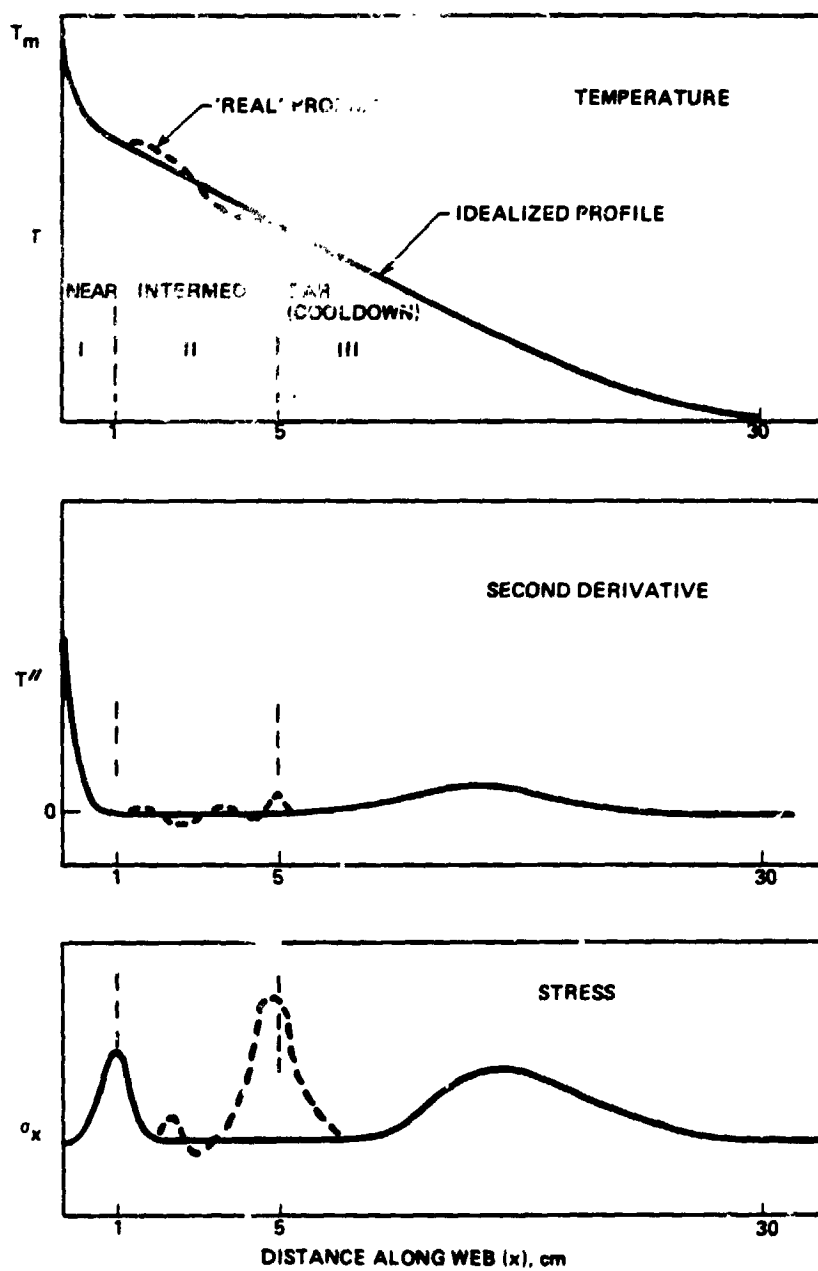
- Model Full Cooling Curve to Analyze Buckling
- Area Rate Currently Not Limited by Interface or Cooldown Stresses
- Intermediate Stress Must be Controlled in Real Systems
- Intermediate Stress
 - Can Trigger Mixed Buckling Mode
 - Direct Cause of Buckles
 - Can Interact to Cause Plastic Flow
- Webs can Grow Continuously in Quasi-Stable Buckled Form

Thermal Stress Regions in Silicon Web



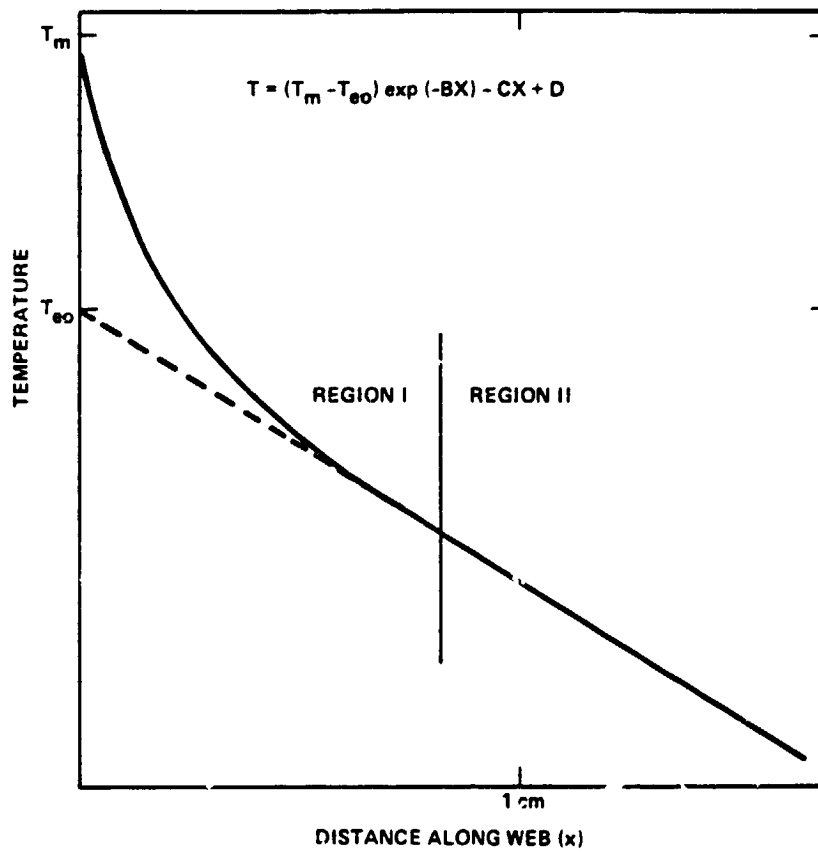
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Web Axial Temperature and Stress Distributions



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Interface Temperature Distribution
(Exponential-Linear)



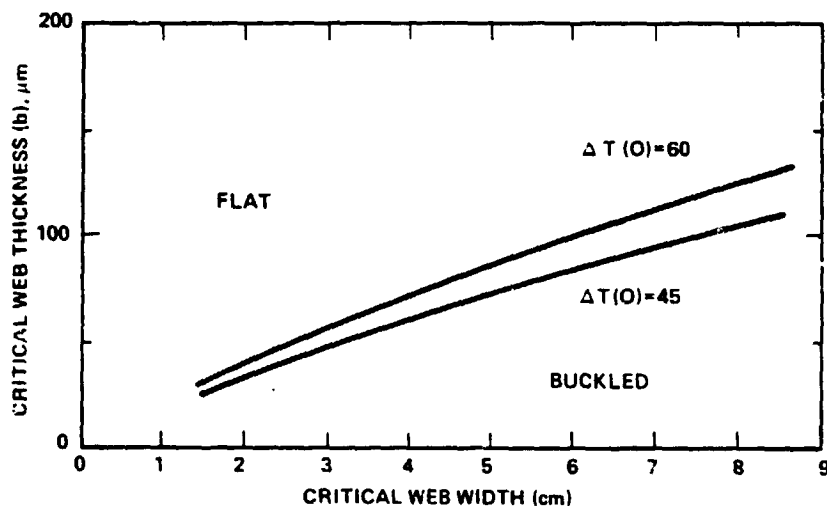
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Near Stress Summary

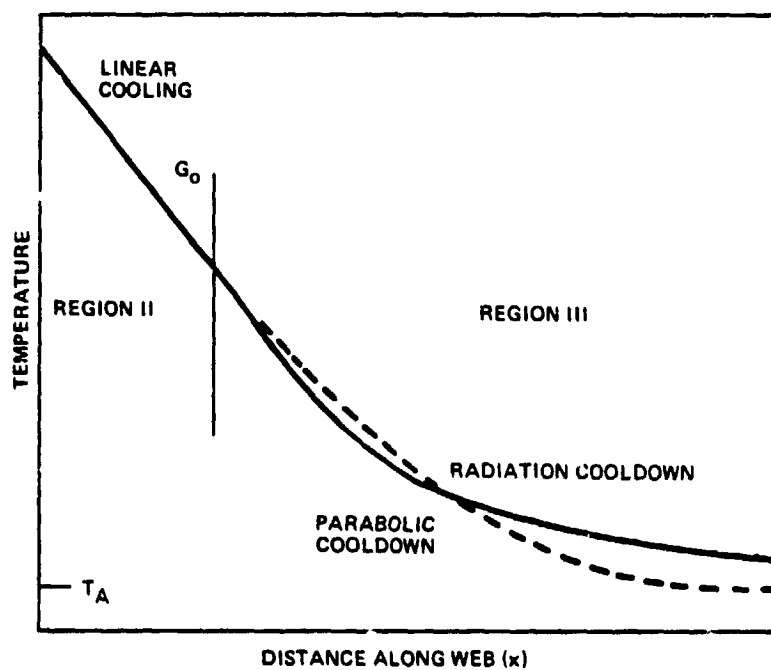
Critical Buckling Thickness And Width Are Related By:

$$b = 1.72 (\Delta T)^{.63} W^{.82}$$

$$\Delta T = (T_m - T_{eo})$$



Cooldown Temperature Curves

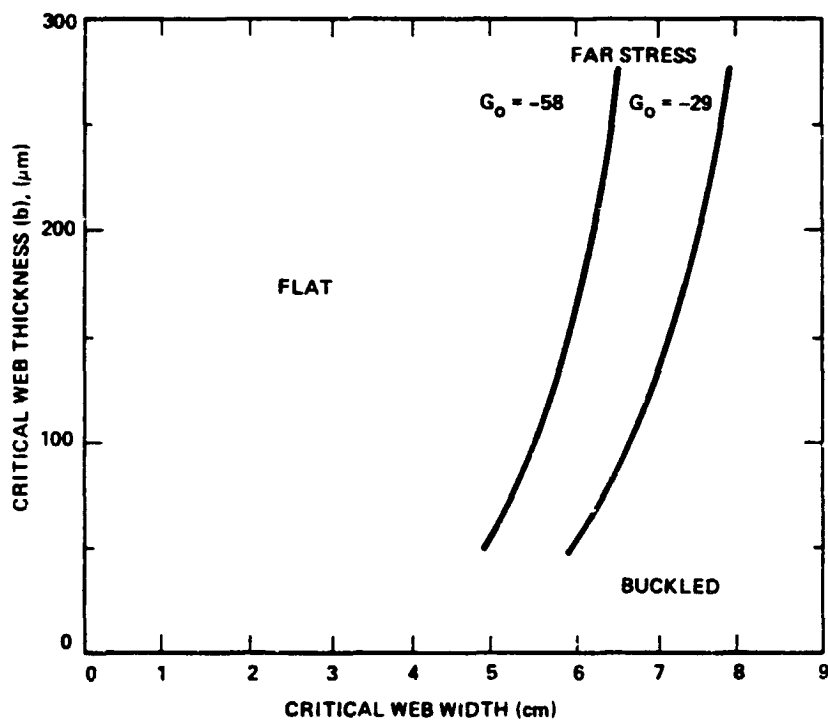


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Far (Cooldown) Stress Summary

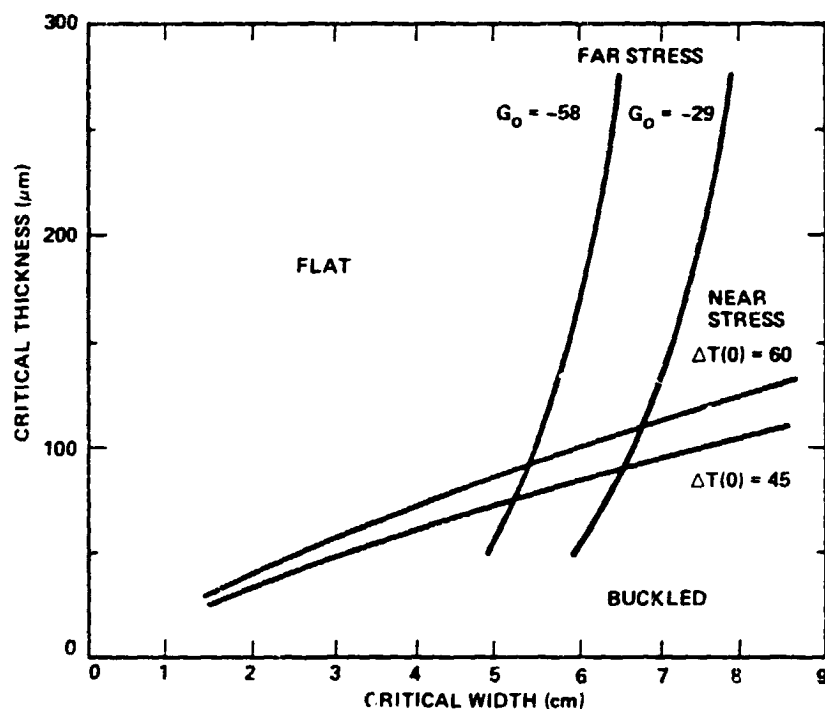
Critical Buckling Thickness And Width Are Related By:

$$b \cong \text{Const. } G_0 W^{3.8}$$



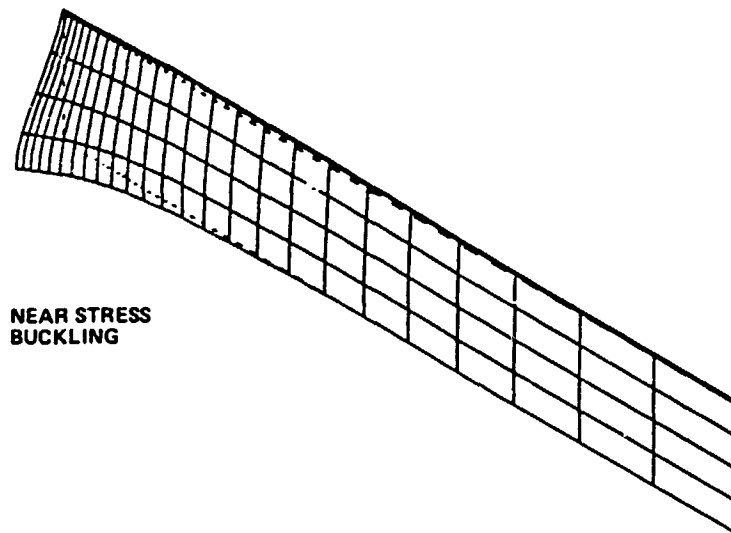
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Parametric Variation of Critical Buckling Width and Thickness

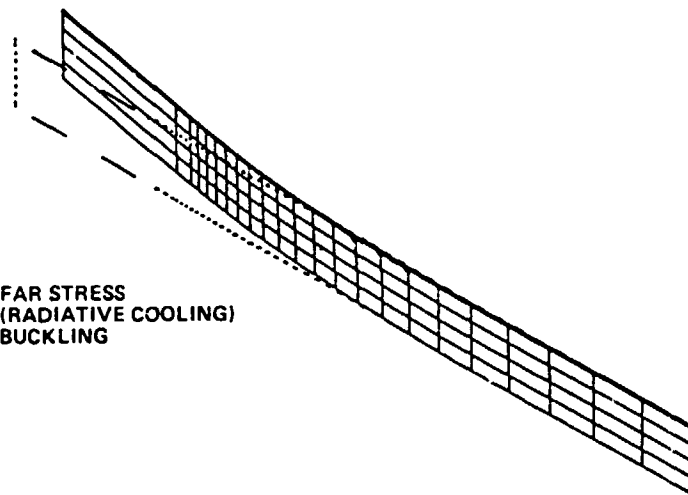


ADVANCED SILICON SHEET

Buckled Web Shapes



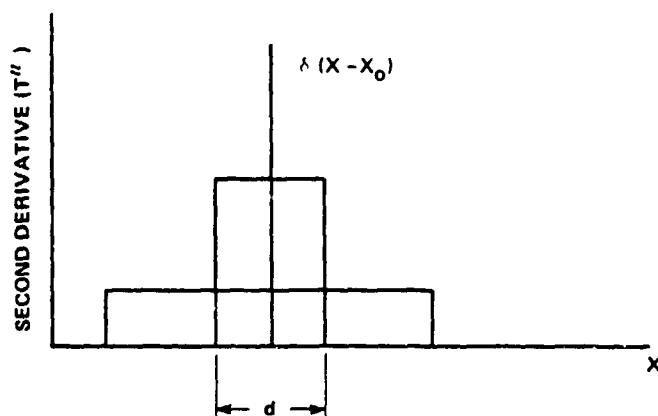
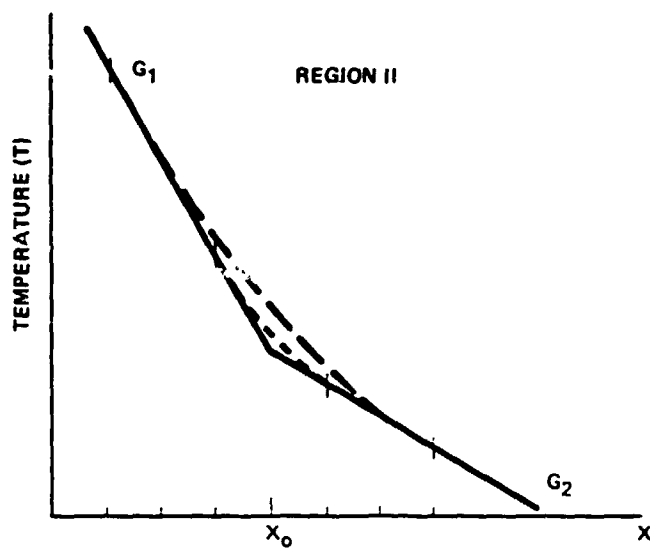
NEAR STRESS
BUCKLING



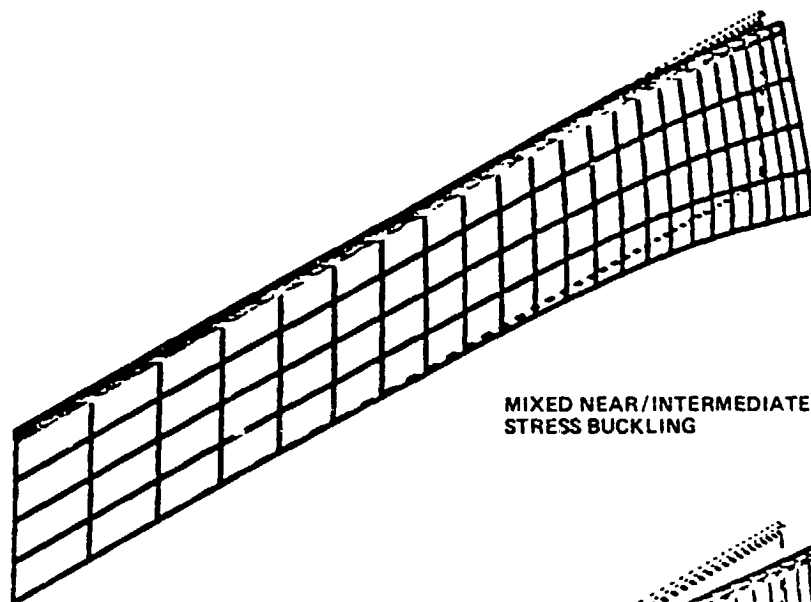
FAR STRESS
(RADIATIVE COOLING)
BUCKLING

ADVANCED SILICON SHEET

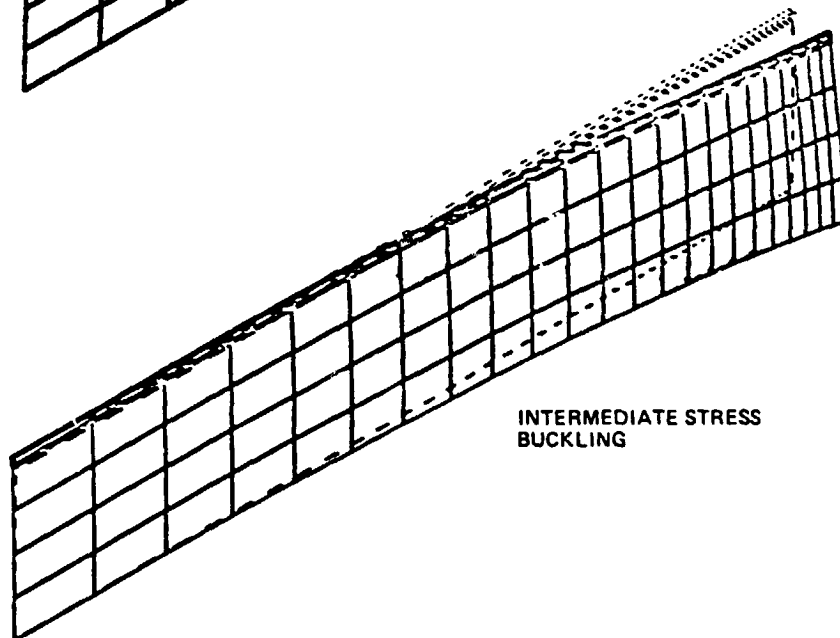
Change in Second Derivative with Bend Transition in Web Temperature Profile



Buckled Web Shapes



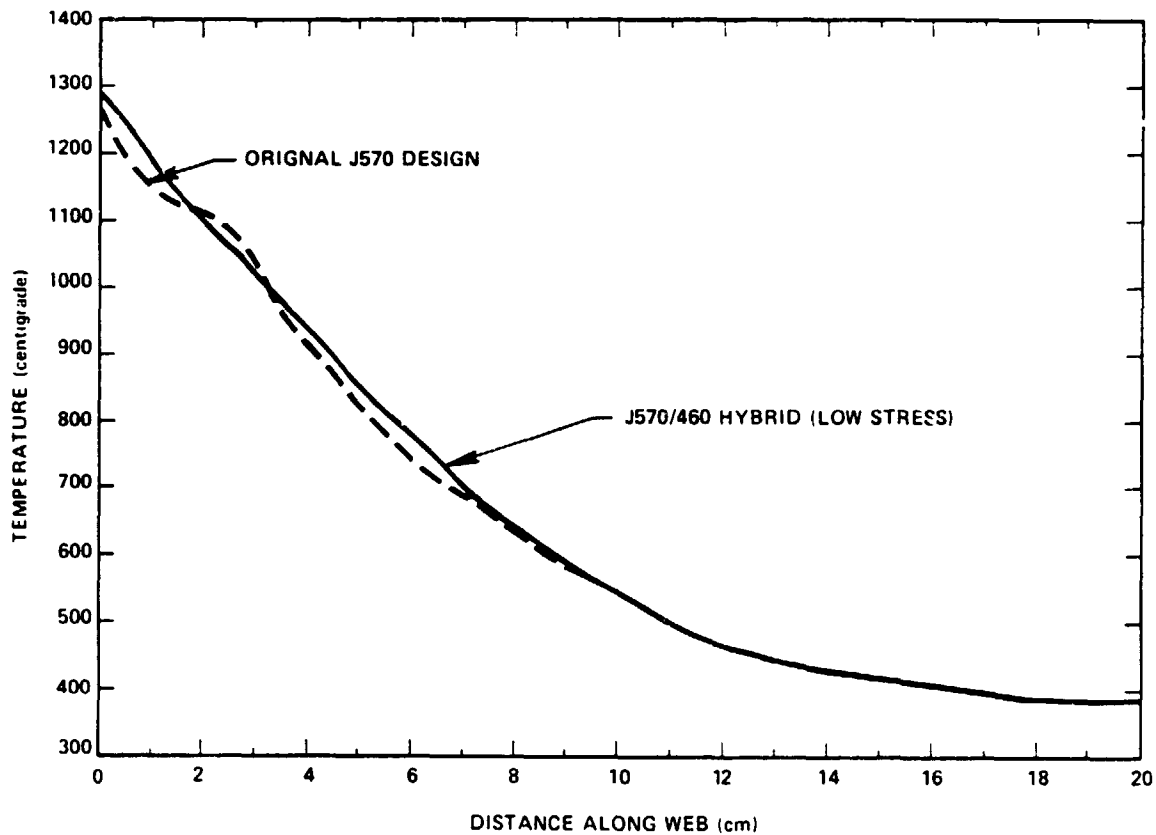
MIXED NEAR/INTERMEDIATE
STRESS BUCKLING



INTERMEDIATE STRESS
BUCKLING

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Improved Linearity in Measured Axial Temperature Profiles



Silicon Dendritic Web Development Modeling Studies

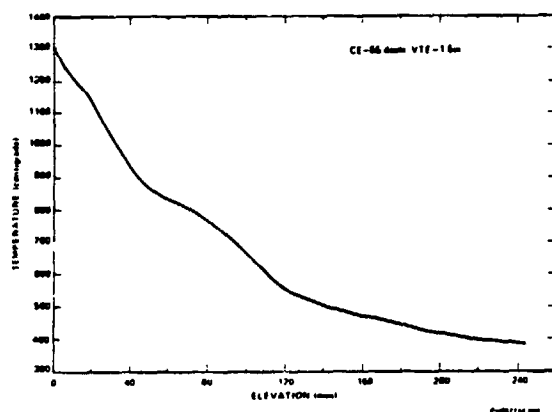
Plastic Deformation

- Penning/Jordan Type Model Developed/Applied to Web
- Predict Defect Distributions in Web
- Residual Stress Estimations in Qualitative Agreement with Experiment
- Residual Stress can Promote/Reduce Buckling
- Plastic Flow Geometry Specific; Controllable by Design

ADVANCED SILICON SHEET

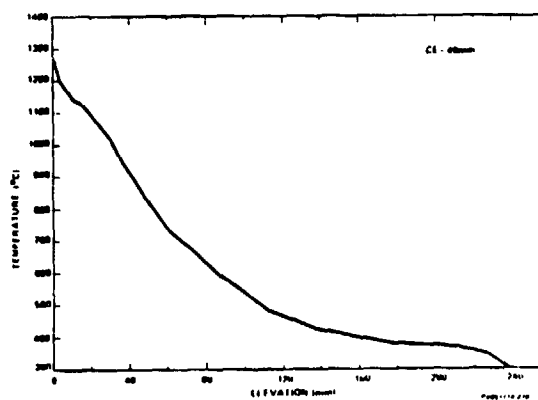
Axial Temperature Profiles Resulting in Widely Different Residual Stress States

THERMAL PROFILE FOR THE J435 CONFIGURATION



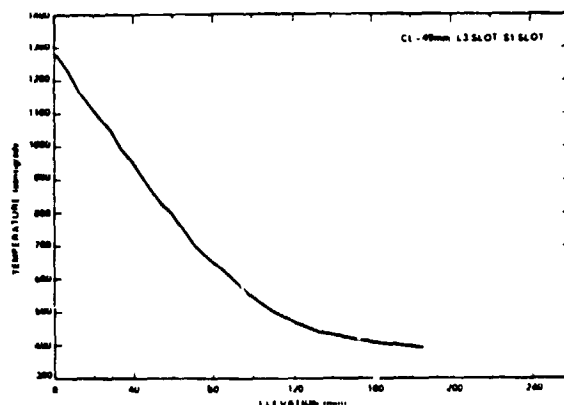
High Positive
Residual Stress

THERMAL PROFILE FOR J570 CONFIGURATION



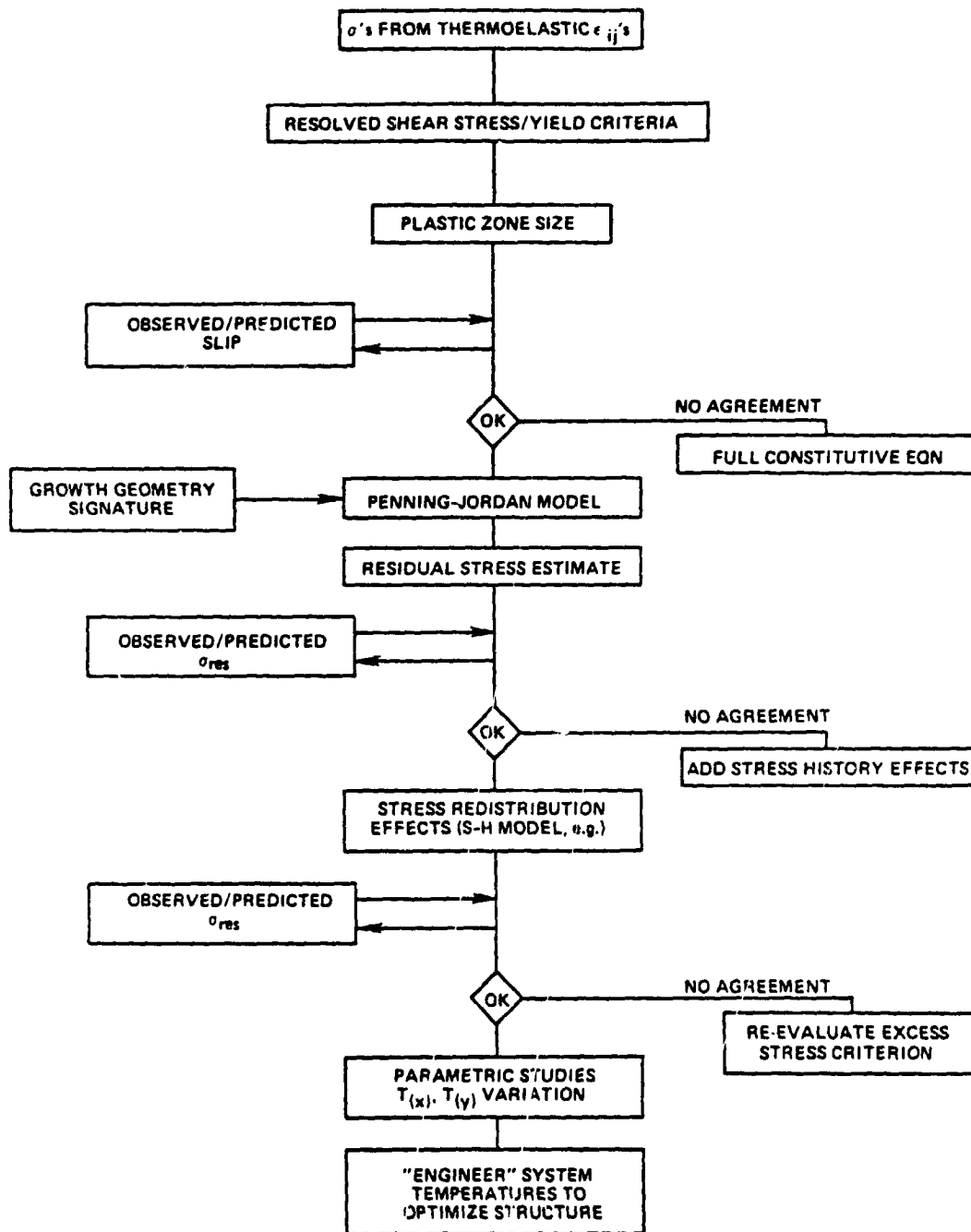
High Negative
Residual Stress

THERMAL PROFILE FOR J570/460 CONFIGURATION



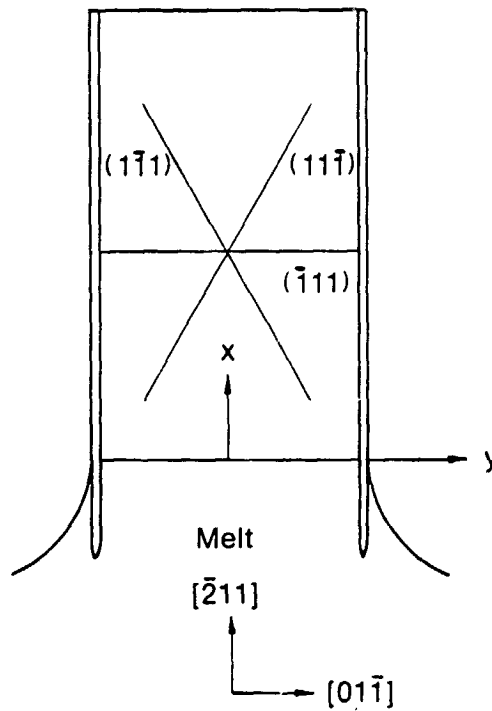
Low (Negative) Residual Stress

Web Plasticity Analysis



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Web Slip Geometry



Plasticity: Penning/Jordan Model

1. Distortions from Thermal Stresses Mostly Elastic
2. Stress Redistribution Effects Small
 - Can Predict Slip Patterns
3. Dislocation Density Proportional to Resolved Shear Stress

$$\rho_a \propto \sum_{x=0}^{x=L} (\tau_a - \tau_y) \Delta x ; y = \text{Const}$$

4. Shear Strain Proportional to ρ_a

$$\epsilon_a \propto \rho_a \cdot b \cdot v$$

$$v = f(\tau_a, T)$$

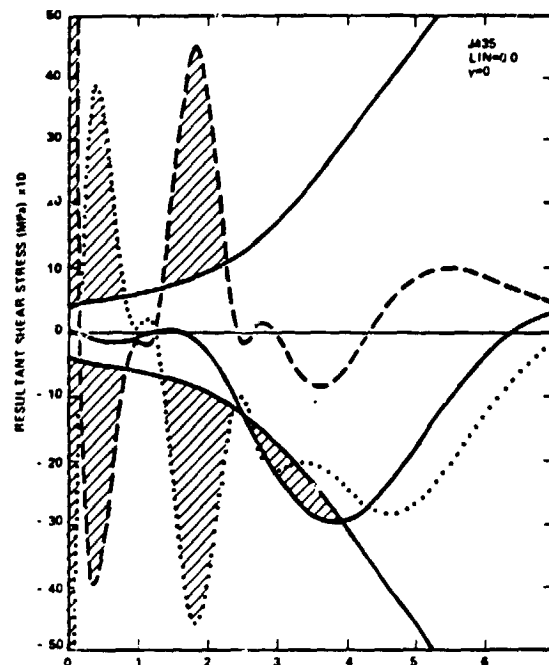
$$\epsilon_a \propto \sum_{x=0}^{x=L} (\tau_a - \tau_y) v \Delta x$$

5. Residual Stress Determined By Net "Plastic" Shear Strain

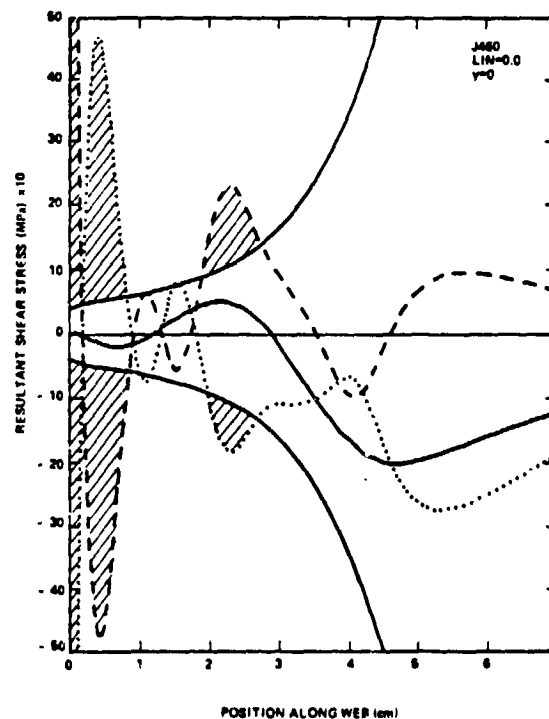
$$\Delta \sigma_x \propto \sum_a \epsilon_a$$

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Resultant Shear Stress Along Web for Various Slip Systems



J435 (5334)



J460

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Comparison of Calculated "Excess Stress" from Model and Measured Residual Stress*

<u>Configuration</u>	<u>Theory at Growth Temp.</u>	<u>Theory T = 300°K</u>	<u>$\Delta \sigma_x$ (Meas) Mdynes/cm²</u>
J435 (5334)	-36.1	+36.1	20-30
J460	+5.6	-5.6	0 \pm 10

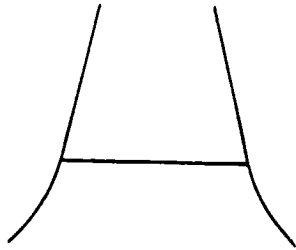
*Not Corrected for Dislocation Velocity Differences

Closed Loop Control Status

- Successful Demonstration of Coupled Coil and Temperature Controls
 - 35% Increase in Crystal Length with Controls
 - Average Dendrite Controlled to $\pm 50 \mu\text{m}$ Control Specification
 - Maximum Controlled Run Length 5.5 Hours (τ System ~ 3 min)
- Experimental Prototype In Place; Operational Data Being Collected

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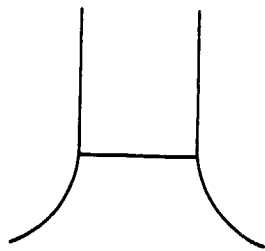
Response of Diameter to Velocity or Temperature Change



Increasing Diameter

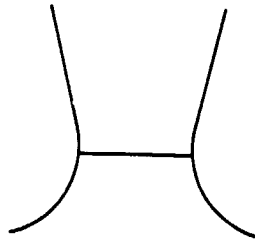
$$T < T_{\text{Growth}}$$

or $V < V_{\text{Growth}}$



Constant Diameter

$$T = T_{\text{Growth}}$$
$$V = V_{\text{Growth}}$$



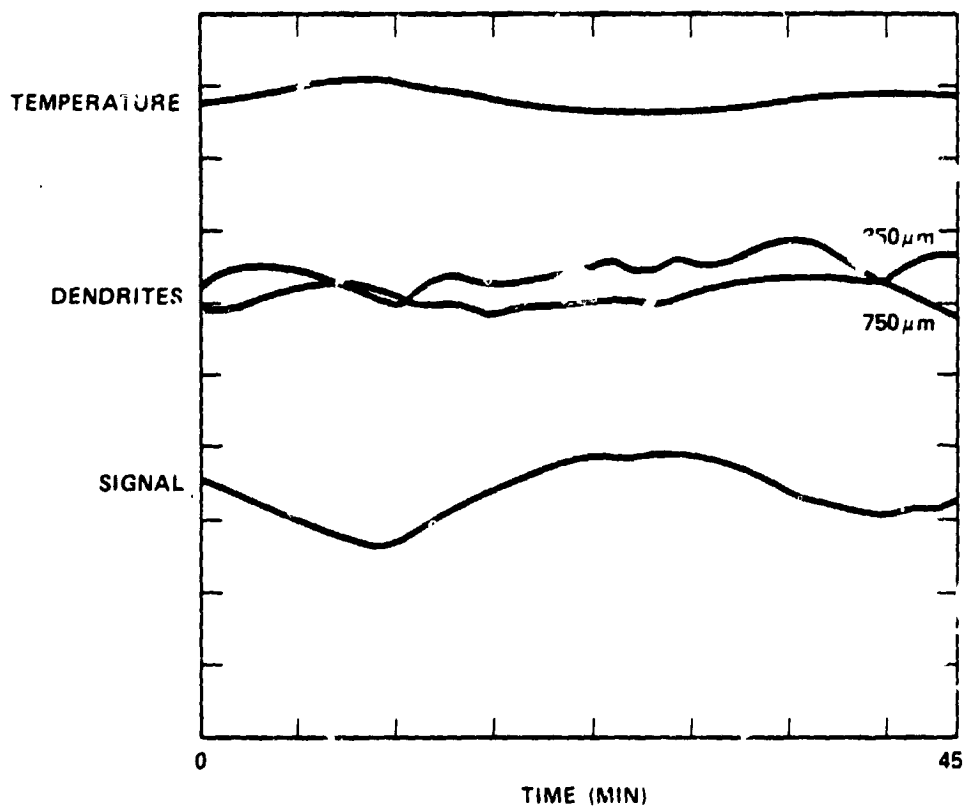
Decreasing Diameter

$$T > T_{\text{Growth}}$$

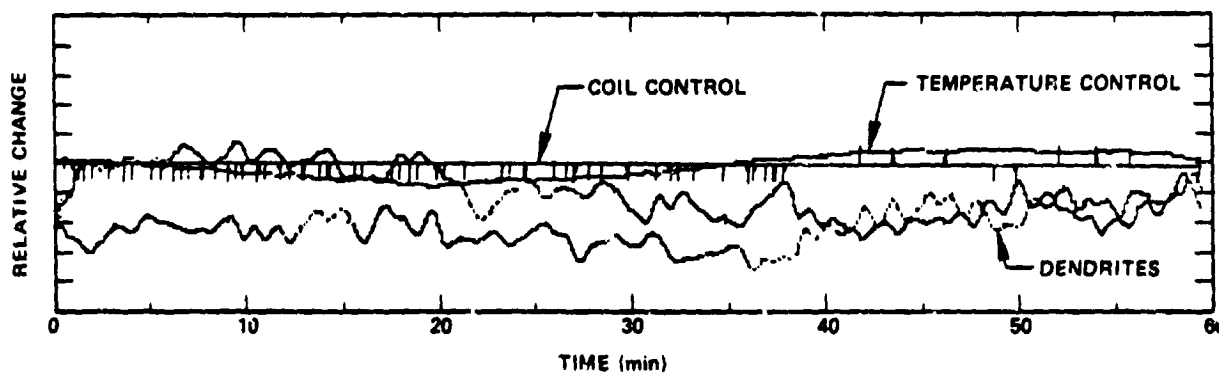
or $V > V_{\text{Growth}}$

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Sample Data from Controlled Growth Run (Control Point = 825)



Coil Positioning Control



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Silicon Dendritic Web Development

Status and Future Activities

- Key Elastic Stress Generation Mechanisms Identified
 - Analytic Focus: Intermediate Stress
Interaction of Near/
Intermediate Stress
 - Experiment Focus: Linearization of
Intermediate Profile
Smooth Cooldown Curve
- General Features of Plastic Flow Appear Predictable
 - Analytic Studies: Refine Flow Model
Parametric Studies
Analyze Elastic/Plastic
Interactions
 - Experiment: Correlation of Observed
Defects/Stress with Model
Engineer Lid Temperature
Profile to Control
Deformation
- Closed Loop Web Growth System Functional
 - Refine Electronics
 - Simplify Hardware and Software
 - Develop Operational Experience to Achieve
Routine Behavior